Exploring B4: A Pulsating sdB star, in a Binary, in the Open Cluster NGC 6791

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ABSTRACT

We report on *Kepler* photometry of the hot sdB star B4 in the open cluster NGC 6791. We confirm that B4 is a reflection effect binary with an sdB component and a low-mass main sequence companion with a circular 0.3985 d orbit. The sdB star is a $g-$mode pulsator (a V1093 Her star) with periods ranging from 2384 s to 7643 s. Several of the pulsation modes show symmetric splitting by 0.62μHz. Attributing this to rotational splitting, we conclude that the sdB component has a rotation period of approximately 9.63 d, indicating that tidal synchronization has not been achieved in this system. Comparison with theoretical synchronization time provides a discriminant between various theoretical models.

Subject headings: open clusters and associations: individual (NGC 6791) — binaries: close — stars: horizontal-branch — stars: oscillations

1. Introduction

Subdwarf B (sdB) stars are evolved low-mass stars that have helium cores surrounded by a thin hydrogen envelope (Saffer et al. 1994). Their effective temperatures range from 22000 to 40 000 K; typical masses are approximately M≈0.47 $M_{\odot}$ (Heber et al. 1984; Heber 2009). Since these stars have survived the core helium flash, they provide an opportunity to study a rapid phase of stellar evolution (Kawaler 2010), and perhaps a direct probe of the post-flash helium core.

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Many sdB stars are non-radial multiperiodic pulsators, which can be used in asteroseismic analysis (Charpinet et al. 2008a; Østensen 2010, and references therein). This analysis can allow us to determine the mass, internal rotation, compositional stratification and other interior properties. There are two main classes of sdB pulsators. The first class to be discovered were the shorter period V361 Hya stars (O'Donoghue et al. 1997) which are primarily $p-$mode pulsators with periods typically between 2-4 minutes. The V 1093 Her stars are g-mode pulsators with periods ranging from 0.75 to 2 h with typical amplitudes of less than 0.1 percent (Green et al. 2003; Østensen 2010). Generally, the pulsation amplitude is higher in the V361 Hya stars (about 1 percent) than in the V1093 Her stars (Kilkenny 2007; Reed et al. 2007).

The formation of stars with such thin surface hydrogen layers (less than 0.1% of the stellar mass) is still not completely understood. There are several proposed formation channels. One channel that has significant observational support involves mass transfer to a companion and ejection of a common envelope (Han et al. 2002, 2003). Observationally, many of the known sdB stars are indeed in close binary systems, with orbital periods on the order of hours (Maxted et al. 2001; Morales-Rueda et al. 2003; Karl et al. 2004; Heber 2009).

Given the short orbital periods, these stars are generally thought to rotate synchronously as the result of tidal effects. However, two theoretical treatments of tidal synchronization provide a range of estimates for the time scale for synchronization (Tassoul 1987; Zahn 1975); for sdB binaries, they can differ by orders of magnitude. B4 provides a potential test of these scenarios. At these rotation velocities, it is not possible to measure rotational broadening in the H or He lines. The narrow metal lines can show broadening, but the lines are very weak, necessitating high resolution and high S/N spectroscopy requiring large telescopes. Therefore, spectroscopic verification of tidal synchronization is difficult, though Geier et al. have addressed this issue with the sdB star PG 0101+039 (Geier et al. 2008). However, asteroseismology provides a possible way to test for synchronization by measuring rotational splitting of oscillation modes. In the few cases where this has succeeded, tidal synchronization seems to be verified: van Grootel et al. (2008) report that the sdB star Feige 48 appears to be in synchronous rotation. It is in a binary with a white dwarf companion, with an orbital and rotation period of 9 h. Another sdB that shows evidence for rotational splitting at the orbital frequency is PG 1336-018 (Charpinet et al. 2008b), with an orbital period of 2.42 h and a low-mass main sequence companion.

These successes have been limited by the difficulty faced by ground-based photometry in resolving the pulsation spectra. *Kepler* provides long-term nearly continuous high-precision photometry, eliminating aliasing problems associated with ground–based data. Early results from *Kepler* observations of sdB stars (Østensen et al. 2010; Kawaler et al.

2010; Østensen et al. 2011, for example) show that *Kepler* provides exquisite time series photometry of these stars. For single g-mode pulsators, the *Kepler* data has already allowed detailed seismic modeling of two sdB stars (van Grootel et al. 2010; Charpinet et al. 2011). These investigations have determined that the mass of the sdB g-mode pulsators is close to what is expected based on standard stellar evolution models. They also place tight constraints on the hydrogen layer thickness for these stars, and indicate that the convective core may be significantly larger than current evolutionary models suggest.

A particularly interesting star that could shed light on the origins of sdB stars is the hot subdwarf B4 in the old open cluster NGC 6791 (Kaluzny & Udalski . 1992). The broadband colors suggested that it was indeed hot enough to be an sdB star. Spectroscopy by Saffer et al. (1994) confirmed it was an sdB star, and that it was likely a member of NGC 6791 based on its spectroscopic distance. B4 was identified as a binary through a significant brightness modulation (Mochejska et al. 2003; de Marchi et al. 2007). However, since no eclipses were seen and the data points were sparse it was not possible to tell whether this was an ellipsoidal or a reflection effect variable.

The temperature determination by Saffer et al. (1994) placed B4 within the range of the V -1093 Her stars, but it had not been observed with a high enough time resolution to detect pulsations. Photometric variations from binary effects and constraints given its membership in NGC 6791, would make it a uniquely valuable asteroseismic target: a nonradially pulsating sdB star, in a close binary, in a cluster. Its presence within a cluster provides stringent constraints on its age (and metallicity) for comparison with models of sdB formation. For example, since the lifetime of an sdB star is short ($\sim 10^8$ yr) compared to the cluster age ($\sim 8 \times 10^9$ yr), the mass of the sdB progenitor must be close to the turnoff mass of 1.1 - 1.2 $M_\odot$. With this potential in mind, B4 was observed as part of the *Kepler* Guest Observer program during Cycle 2.

In this paper we report the discovery of multiperiodic $g-$mode pulsation in B4. We confirm that it shows a longer period variation associated with a reflection of light from a companion with a much lower temperature. This variation signals an orbital period for the binary system of 0,3985 d. Our analysis of the pulsations reveals that the sdB star is *not* in synchronous rotation. We also estimate the synchronization time scale using two prescriptions for tidal spin-up, and show that the results favor that of Zahn (1975) but are dependent on the details of the structure of the sdB star.

2. Observations

While the primary mission of the *Kepler* spacecraft is the search for extrasolar planetary transits (Koch et al. 2010; Borucki et al. 2010), it is also very well suited for asteroseismic observations (Gilliland et al. 2010a). Observations of B4 were obtained in late 2010 and early 2011 by the *Kepler* spacecraft during Cycle 2 of the the GO program. In this paper, we analyze the first 6 months of data (Q6 and Q7) on this star. The data were taken at the short cadence (SC) mode, with individual integrations of 58.85 s. The data acquisition and pipeline reductions are as described in Gilliland et al. (2010b) and Jenkins et al. (2010). The data coverage is continuous except for short, monthly gaps for data retrieval and occasional brief safe mode events. The data pipeline produces both a raw and "corrected" flux value for each integration. Since the corrected value accounts for estimated background contamination (which may change with follow-up photometry in the future), we use the raw flux. For analysis of the photometric variations, we quote fractional variation from the mean flux.

We removed outliers beyond 4 times the RMS deviation from the local mean (determined via a boxcar filter with a width larger than any expected pulsation but smaller than the timescale for binary variation). This filtering removed 225 points from the original data. B4 has a V magnitude of 17.87 (de Marchi et al. 2007) and a *Kepler* magnitude (K_p) of 18.27. The noise level is approximately 3.4×10^{-2} per integration; in 6 months of data, this reduces to a noise level of 6.7×10^{-5}.

3. Analysis

3.1. Binary Variation

This star is quite faint even for *Kepler*, so to establish a binary ephemeris we use phased data to get a better sense of the overall light curve shape. We found each point of maximum, rather than keying on another phase, because the light curve shows more sharply–peaked maxima and the time of each maximum could be defined more precisely than the flatter minimum. We assumed that the period did not change on time scales smaller than days. This allowed us to add several days of data together with a block-phasing procedure. We achieved the best results by averaging over 10 orbital cycles. Using this procedure we found the period to be 0.3984944(35) d and T0 to be 55372.6002(9) (in BJD - 2400000).

If this modulation is caused by ellipsoidal variation, then the period of 0.3985 d would represent one half of the orbital period, since in an ellipsoidal variable, there are two minima and two maxima per orbit. Furthermore, ellipsoidal variables often display minima of unequal

depth (Hutchings 1974; Wilson & Sofia 1976; Bochkarev et al. 1979), producing a peak in the Fourier transform at the subharmonic of the highest-amplitude periodicity.

Figure 1 shows the light curve phased at twice the period determined above.This light curve shows minima of equal depth, and maxima of equal height. There are no eclipses apparent. In the Fourier transform of the light curve, the largest amplitude peak corresponds to the 0.3985 d period, and the next–highest frequency peak corresponds to the first harmonic of this orbital period. We note that the frequency of the first harmonic of the orbital period (in Table 1) is slightly more than 1 σ away from exactly $2 \times f_{\rm orb}$. We do not think that this difference is significant. We see no significant peak at the subharmonic.

We conclude that the observed variation is caused by the reflection effect, with the light from the sdB star illuminating a cooler and fainter companion. Thus the period of the binary is 0.3984944(35) d. A radial velocity curve for this star should therefore show a period of 0.39849 days. In addition, radial velocity observations would constrain the mass ratio of the system.

3.2. Pulsation

The Fourier transform of the $g-$mode region, with the peaks identified, is shown in Figure 2. B4 shows many periodicities in the frequency range from 120 to 420 μHz, which are characteristic of $g-$mode pulsation in V 1093 Her stars. We followed the "standard" procedure of successive removal of periodicities by nonlinear least-squares fitting of sinusoidal signals at the frequency peaks (see Kawaler et al. 2010, and references therein). Each successive prewhitening was performed in the time domain. We continued this process until no peaks remained at or above 4 times the RMS noise level in the residuals. This 4-σ limit was 0.29 parts per thousand (ppt). Above this we found 16 unique frequencies which are given in Table 1. There are 3 more frequencies near the detection threshold which await confirmation with further data, but we include them in Table 1 for reasons noted below.

The g-mode period distribution in B4 resembles, quite closely, that seen in non-binary sdB pulsators. In high–overtone $g-$mode pulsators (where $n >> l$), the periods of consecutive overtones should be equally spaced, with a period spacing that scales with $1/\sqrt{l(l+1)}$. Here, we use the standard labeling of nonradial modes, where n, l, and m are the radial, angular, and azimuthal quantum numbers. This behavior is seen in pulsating white dwarf stars (e.g., Winget et al. 1991, 1994) and in g-mode sdB pulsators (Reed et al. 2011). For the sdB stars observed by *Kepler* the period spacings range from 231 s to 272 s, with that spacing identified with l=1 modes (Reed et al. 2011).

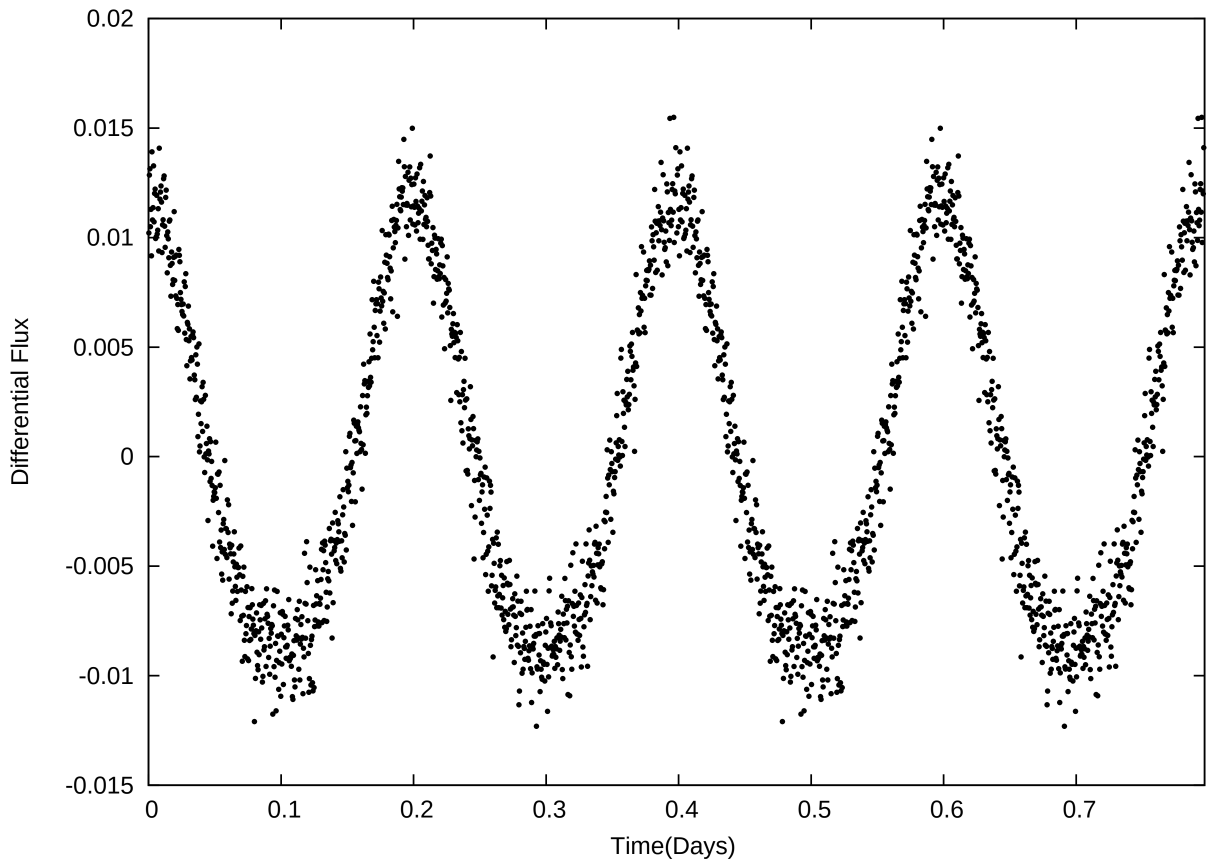

Fig. 1.— Photometric data on B4, phased on twice the suspected orbital period (2×0.3885 d). The equal–depth mimina rule out ellipsoidal variation.

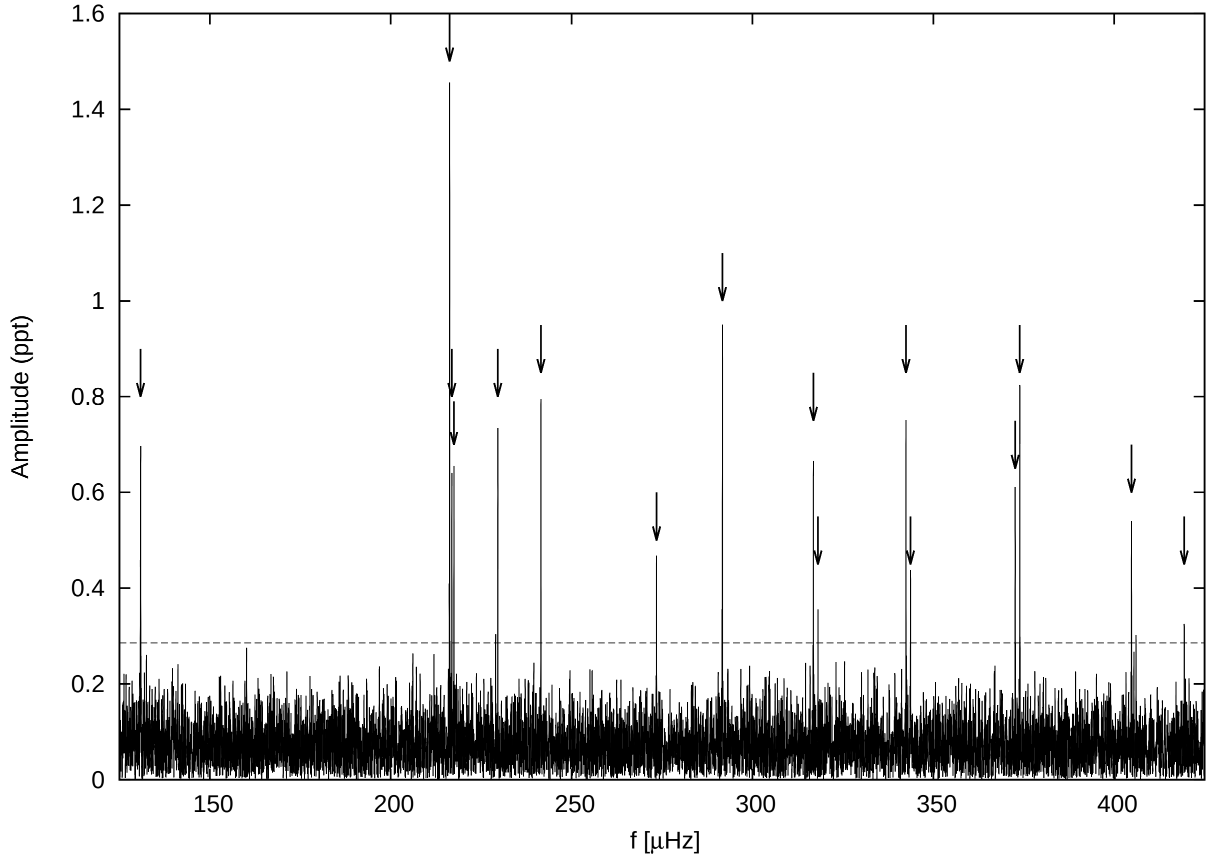

Fig. 2.— The g-mode region of B4. The arrows show all pre-whitened frequencies The 4 σ level above the noise is represented by the dotted line.

Table 1. Periodicites of B4. Quoted errors are formal least-squares errors.

ID	Frequency [μHz]	Period [s]	Amplitude [ppt]	Orbital splitting	fine structure
	Binary period and first harmonic				
f_{orb}	29.04430 ± 0.00022	34430.17 ± 0.26	10.310 ± 0.064		
$2f_{orb}$	58.0901 ± 0.0014	17214.63 ± 0.42	1.579 ± 0.064		
			Pulsation frequencies		
f1	130.8784 ± 0.0032	7640.68 ± 0.19	0.700 ± 0.064		
f2	216.2851 ± 0.0016	4623.527 ± 0.034	1.427 ± 0.064		
f3	216.8996 ± 0.0038	4610.428 ± 0.068	0.081 ± 0.064		= f2+0.615
f4	217.4811 ± 0.0036	4598.101 ± 0.076	0.631 ± 0.064		= f3+0.582
f5[1]	229.0105	4366.61	0.314		
f6	229.6014 ± 0.0031	4355.374 ± 0.058	0.740 ± 0.064		= f5+0.591
f7	241.5107 ± 0.0028	4140.604 ± 0.048	0.800 ± 0.064	= f3+24.60	
f8	273.4754 ± 0.0048	3656.637 ± 0.065	0.467 ± 0.064	=f7 +2×15.98	
f9	291.7086 ± 0.0024	3428.079 ± 0.028	0.948 ± 0.064		
f10	316.8387 ± 0.0034	3156.180 ± 0.034	0.664 ± 0.064		
f11	318.1220 ± 0.0062	3143.448 ± 0.062	0.363 ± 0.064		= f10+1.283
f12	342.4285 ± 0.0030	2920.318 ± 0.026	0.744 ± 0.064	= f11 + 24.27	
f13	343.7004 ± 0.0052	2909.511 ± 0.044	0.432 ± 0.064		= f12+1.272
f14	372.6323 ± 0.0037	2683.611 ± 0.027	0.613 ± 0.064		
f15	373.8966 ± 0.0027	2674.536 ± 0.020	0.828 ± 0.064	=f12+2×15.73	= f14+1.264
f16	404.7753 ± 0.0042	2470.506 ± 0.026	0.538 ± 0.064	=f15+2×15.44	
f17[1]	405.45	2466.4	0.27		=f16+0.68
f18[1]	406.04	2462.81	0.307		=f17+0.61
f19	419.3662 ± 0.0069	2384.551 ± 0.039	0.325 ± 0.064		

[1]Frequencies near the detection threshold; not included in the fit.

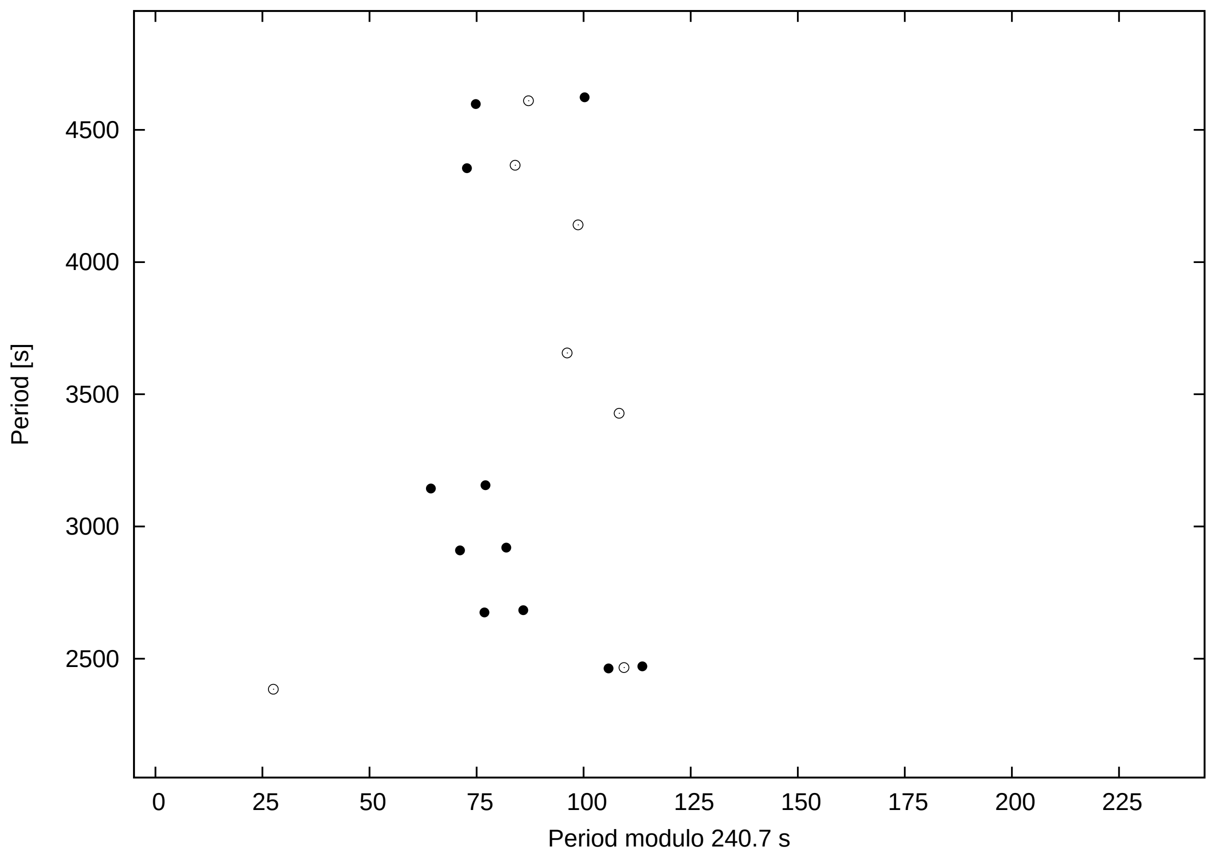

Fig. 3.— Echelle diagram of the periodicities f2-f18 of B4 with a folding period is 240.7s. Filled circles are suspected $m = \pm 1$ modes, and open circles are $m = 0$ modes (or modes for which m cannot be determined).There is a clear ridge around 85 s.

Figure 3 shows that B4 also follows this trend. This echelle diagram plots points associated with each periodicity; the vertical axis is the period and the horizontal axes is the period modulo the average period spacing of 240.7 s. For equally–spaced modes, the periodicities should line up vertically, with (small) departures to be expected as a result of mode trapping by composition gradients within the star. The "best" period spacing of 240.7 s is in very close accord with l=1 pulsations in sdB stars (Reed et al. 2011). One periodicity, f1 (P=7640 s), does not lie near the ridge (it would be at at 226 s on the abscissa of Figure 3). Another lower amplitude mode, f19, also does not fall along the ridge.

As indicated in Figure 3 there are multiple periodicities for a given order in the diagram (i.e. 3 successive, nearly horizontal points). This multiplet structure results from rotational splitting: nonradial modes with the same values of n and l can be split into equally spaced multiplets by rotation, with the frequency splitting proportional to the rotation frequency. The well–known relationship between frequency splittings and rotation (see, for example Ledoux 1951), is

$$f_{n,l,m} = f_{n,l,0} + m\Omega(1 - C_{n,l}) \tag{1}$$

where Ω is the (assumed solid-body) rotation frequency, and $C_{n,l}$ is the Ledoux constant, For B4, we adopt values for $C_{n,l}$ from Kawaler et al. (2010) of 0.48 for $l = 1$ and 0.16 for $l = 2$ modes.

As can be seen in Figure 2 and in the table, there is one well-defined triplet in the data with an average spacing of 0.60 μHz consisting of f2, f3, and f4. Triplets are expected for rotational splitting of l=1 modes. We also see many doublets with spacing of nearly twice that value: (f10, f11), (f12, f13), and (f14, f15), along with two peaks separated by 0.59 μHz (f5, f6). Taken together, these multiplets, if l=1, indicate a rotation frequency of 1.20 μHz, (a rotation period of 9.63 d). The structure of the amplitude spectrum surrounding each of these frequencies is shown in Figure 4.

B4 is a close binary; if in synchronous rotation, we would expect to see splittings that are approximately 15.4 μHz for $l = 1$ modes and 24.4 μHz for $l = 2$ modes. The measured splittings are much smaller than this orbital frequency, leading to the surprising conclusion that the sdB component is most likely not in synchronous rotation. Though one might expect the system to be in complete spin–orbit resonance, with the sdB rotating at the orbital frequency, this does not seem to be the case.

The fifth column of Table 1 shows that some of the frequency spacings between periodicities approach the orbital frequency. This is, we believe, the result of an unfortunate coincidence: the average *period* spacing between $g-$modes of 240 seconds corresponds to a *frequency* spacing ranging from 11.3 μHz at the long-period end to 34 μHz at the short period side. Thus some of the apparent frequency spacings that might match those ex-

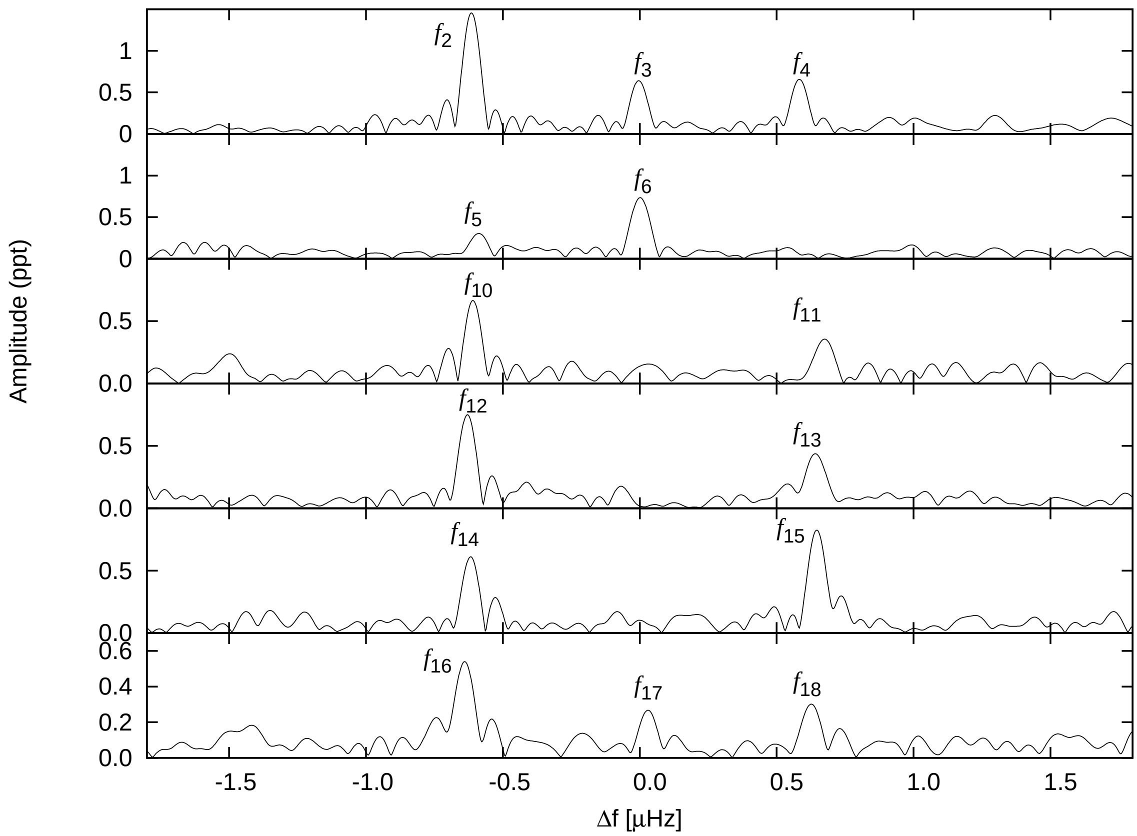

Fig. 4.— Amplitude spectrum of several g-modes in B4, centered on the suspected rotational multiplets. The frequencies of each peak can be found with corresponding labels in Table 1. There is one triplet (top) with an average spacing of 0.6 μHz. Several doublets show twice this splitting. Some of these doublets show signs of a peak halfway in between enhancing the likelihood that 0.6 μHz is the rotational splitting.

pected for synchronous rotation arise instead as a consequence of equal period spacings for high-overtone $g-$modes.

3.3. Synchronization time scales

Recent seismic studies of sdB binary systems with short periods suggest that they are in synchronous rotation; e.g. Charpinet et al. (2008b) and van Grootel et al. (2008) looked at systems with orbital periods of 2.42 h and 9.02 h respectively. Geier et al. (2008, 2010) claim synchronous rotation in systems with orbital periods up to 14h. But B4, with an orbital period of 9.56 h does not rotate synchronously.

There are two prescriptions to calculate the time scale for synchronization: Tassoul (1987, 1988) and Zahn (1975) . Tassoul (1987, 1988) argue that large meridional currents driven by tidal effects can drive changes in the rotation rate in nonsynchronous systems. For stars with radiative envelopes, Claret et al. (1995) provides an estimate for the Tassoul (1988) synchronization time:

$$\tau_{\rm syn} = 2.13 \times 10^4 yr \left(\frac{1+q}{q}\right) \left(\frac{L}{L_\odot}\right)^{-1/4} \left(\frac{M}{M_\odot}\right)^{5/4} \left(\frac{R}{R_\odot}\right)^{-3} \left(\frac{P}{\rm days}\right)^{11/4} \quad (2)$$

where q is the mass ratio of the system (assumed to be close to 1), and P is the binary period. For parameters typical of sdB stars ($M = 0.48 M_\odot$, $R \approx 0.2 R_\odot$, $L \approx 30 L_\odot$), $\tau_{\rm syn} \approx 2 \times 10^5$ y for $P = 0.4$d, assuming a mass ratio of 1. We would thus expect B4 to be synchronous since it has an evolutionary time scale that is a factor of 500 times longer. While the Tassoul (1988) prescription is not easily extended to low mass ratios, a mass ratio of 0.2 used in Equation 2 yields a synchronization time that is still short compared to the evolutionary time scale.

Zahn (1975), explores how tides couple to non-radial oscillations in the star. The oscillations propagate through the convective core and the radiative zone, and provide a torque. For stars with radiative envelopes, the resulting synchronization time scale, from Claret & Cunha (1997) can be written as

$$\tau_{\rm syn} = 3.43 \times 10^6 yr \left(\frac{\beta}{0.13}\right)^2 \left(\frac{1+q}{q}\right)^2 \left(\frac{M}{M_\odot}\right)^{7/3} \left(\frac{R}{R_\odot}\right)^{-7} \left(\frac{P}{\rm days}\right)^{17/3} \left(\frac{E_2}{10^{-8}}\right)^{-1} \quad (3)$$

where β the "radius of gyration" (the moment of inertia, I scaled by MR^2) and E_2 is a tidal constant for a given stellar structure. E_2 depends sensitively on stellar structure, and in particular on the fractional size of the convective core. For large cores, E_2 can reach values of 10^{-5}; for small convective cores, its value approaches zero (see Claret 2004).

Though we do not have values for E_2 calculated directly for sdB models, Claret (2004) provides E_2 for convective core burning main-sequence models with similar convective core mass fractions to the sdB stars (approximately 0.14). Though the sdB stars burn helium in the core, the presence or absence of convection is the most important factor for tidal coupling. Claret (2004) main sequence models with that size core generally have values of E_2 between 5×10^{-9} and 1.3×10^{-8}, somewhat independent of mass. We choose 10^{-8} as a representative value. Using the same representative values for mass, radius, and orbital period, Equation 3 provides $t_{syn} \approx 10^9$ yrs for $q = 1$. For a lower-mass companion (lower q), the time scale is even longer. We note that for Equation 3 to reduce to 10^8 yr for B4, E_2 would need to be $\approx 10^{-7}$. For sdB stars with a comparable orbital period but more massive companion (i.e. Feige 48), synchronization should be swifter than for B4.

This leads us to the conclusion that the Zahn (1975) mechanism may be slow enough to allow the B4 binary to be out of spin-orbit synchronization. However, conclusive analysis requires direct calculation of E_2 for evolutionary stellar models at the correct $T_{\rm eff}$ and $\log g$.

4. Discussion

The hot blue subdwarf B star, B4, in the old open cluster NGC 6791 is a pulsating member of a short-period reflection-effect binary with an orbital period of 0.3984944(35) d. Frequency splittings in the g-mode pulsation spectrum reveal that the sdB component rotates with a period of 9.63 d, and therefore is not in synchronous rotation. The nearly–equal period spacings resemble the pattern seen in many other g-mode sdB pulsators being observed with *Kepler*. Thus the *Kepler* sdB pulsators form a homogenous class, independent of their binarity.

B4's membership in NGC 6791 provides its (overall) age and metallicity; its initial main sequence mass is close to the turnoff mass of $1.15 M_\odot$. Further asteroseismic probing subject to these initial constraints should provide a new opportunity to address the riddle of the formation of sdB stars in general. Given that B4 is not in synchronous rotation, it will be important to compute the synchronization time scale for sdB stars in close binaries to evaluate the accuracy of current theoretical models of tidal synchronization. A spectroscopic determination of $T_{\rm eff}$ and $\log g$ (as well as the mass ratio of the system) is essential for this.

We plan continued photometric monitoring of B4 with *Kepler* for as long as possible. In addition to refining the observed frequencies, increasing S/N could reveal lower-amplitude modes, allowing us to fill out the l=1 pulsation spectrum and expose modes with higher values of l. In addition, extended photometry may allow us to measure the evolution of the

sdB component through secular period changes as the star continues its nuclear evolution. If it is a newly–formed sdB star that is experiencing tidal spin-up, we may also be able to measure the increasing rotational frequency through the pulsations.

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